UNIVERSALLY ORIENTED RENEWABLE LIQUID MIRROR

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[0001]   The United States Government has rights in this invention pursuant to

Contract No. W-7405-ENG-48 between the United States Department of Energy and

the University of California for the operation of Lawrence Livermore National

Laboratory.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002]   This application claims the benefit of U.S. Provisional Application No.

60/258,192, filed 12/22/2000, and entitled "Renewable Thin-Liquid-Film Reflecting

Apparatus," which is incorporated herein by this reference. U.S. Patent Application

No. xx/xxx,xxx, filed 12/xx/2001 entitled "Renewable Thin-Liquid-Film Reflection

Grating" and U.S. Patent Application No. xx/xxx,xxx, filed 12/xx/2001 entitled

"Renewable Thin Film Liquid Reflecting Zone Plate" describing related inventions

are being filed simultaneously with this application. The specification, drawings,

and disclosure of U.S. Patent Application No. xx/xxx,xxx, filed 12/xx/2001 entitled

"Renewable Thin-Liquid-Film Reflection Grating" and U.S. Patent Application No.

xx/xxx,xxx, filed 12/xx/2001 entitled "Renewable Thin Film Liquid Reflecting Zone

Plate" are incorporated herein by this reference.

BACKGROUND

Field of Endeavor

[0003]   The present invention relates to mirrors and more particularly to a universally oriented liquid mirror.

State of Technology

[0004]   An arbitrarily oriented mirror is an important element of an optical system. It allows an arbitrary transformation of a light beam. There exist high quality solid mirrors, both planar and shaped which can be arbitrarily oriented in the gravity field. However, in applications where one deals with high-power pulses of radiation these mirrors will be damaged and would require replacement after every pulse, introducing significant operational expenses. There exists also planar and parabolic (rotating) liquid mirrors, as well as liquid mirrors controlled by j×B forces, but these mirrors are suitable only for a specific ("face up") orientation in the gravity field.

SUMMARY

[0005]   Features and advantages of the present invention will become apparent from the following description. Applicants are providing this description, which includes drawings and examples of specific embodiments, to give a broad representation of the invention. Various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this description and by practice of the invention. The scope of the invention is not intended to be limited to the particular forms disclosed and the

invention covers all modifications, equivalents, and alternatives falling within

the spirit and scope of the invention as defined by the claims.

[0006]   The present invention provides a universally oriented liquid mirror.

The mirror comprises a liquid and a penetrable unit. A system operatively

connects the liquid to the penetrable unit to provide a mirror that can be

universally oriented.

[0007]   The invention is susceptible to modifications and alternative forms.

Specific embodiments are shown by way of example. It is to be understood that

the invention is not limited to the particular forms disclosed. The invention

covers all modifications, equivalents, and alternatives falling within the spirit

and scope of the invention as defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008]   The accompanying drawings, which are incorporated into and

constitute a part of the specification, illustrate specific embodiments of the

invention and, together with the general description of the invention given

above, and the detailed description of the specific embodiments, serve to explain

the principles of the invention.

FIG. 1 illustrates an embodiment of a planar renewable mirror system.

FIG. 2 shows a liquid film over a solid substrate.

FIG. 3 depicts dispersion curves for capillary oscillations of mercury film

of various depths.

FIG. 4 depicts dispersion relation presented in the dimensionless form.

FIG. 5 illustrates creating a quasi-planar mirror by an electrostatic correction of the meniscus.

FIG. 6 illustrates creating a focusing mirror by electrostatic forces acting on the surface of a conducting fluid, with a control electrode situated above the mirror surface.

FIG. 7 illustrates creating a focusing mirror by electrostatic forces acting on the surface of a dielectric fluid, with a control electrode situated underneath the solid substrate.

FIG. 8 illustrates the possibility of creating a tilted renewable planar mirror by compensating the gravity force by a j×B force in a conducting fluid.

FIG. 9 illustrates another embodiment of a system incorporating the present invention.

FIG. 10 illustrates an additional embodiment of a system incorporating the present invention.

FIG. 11 illustrates an additional embodiment of a system incorporating the present invention.

FIG. 12 illustrates creating a shaped renewable liquid mirror by using a shaped substrate.

DETAILED DESCRIPTION OF THE INVENTION

[0009]   Referring now to the drawings, to the following detailed information, and to incorporated materials; a detailed description of the invention, including specific embodiments, is presented. The detailed description serves to explain the

principles of the invention. The invention is susceptible to modifications and

alternative forms. The invention is not limited to the particular forms disclosed.

The invention covers all modifications, equivalents, and alternatives falling

within the spirit and scope of the invention as defined by the claims.

[0010] Referring now to FIG. 1, an embodiment of a system incorporating the

present invention is illustrated. The system is generally designated by the

reference numeral 10. The system 10 is a planar renewable universally oriented

liquid mirror. The planar renewable mirror system is shown with an upside-

down orientation in FIG. 1. The universally oriented liquid mirror 10 includes a

liquid 11 contained by a porous unit 12. The porous unit 12 maintains operability

of the liquid mirror 10 in all orientations.

[0011] The liquid film planar renewable mirror system 10 illustrated in FIG. 1

will now be described in greater detail. A system for creating liquid mirrors for

X-ray and optical wavelengths that can be arbitrarily oriented with respect to

gravity is provided and used to produce the liquid film planar renewable mirror

10. The system uses a porous substrate 12, ~1 mm thick. A piston 15 presses the

working fluid through the substrate, creating a liquid film with a thickness,

which is a few times the diameter of the characteristic pore size. Capillary forces

in combination with viscous damping smooth all small-scale non-uniformities

and create a surface of an optical quality. After the passage of the optical pulse,

the film is pulled back by reversing the piston and the same sequence is

repeated. The time for the in-out motion of the fluid will be shorter than the time

for the film to flow under the action of gravity. For the "upside-down" configuration, the in-out time must be also shorter than the e-folding time for long-wavelength, Rayleigh- Taylor unstable perturbations. For centimeter-size mercury mirrors, 30 micron thick, the in-out time can be as long as 0.1 s. By shaping the surface of the porous substrate, one can create curved mirrors. In some configurations, the gravity-driven flow can be suppressed by driving the current through the film and stopping the gravity-driven flow by the JxB force.

[0012] The mirror 10 is particularly useful in situations where a conventional mirror would experience problems. The 3rd generation light sources, such as the Advanced Photon Source at Argonne National Laboratory, are capable of providing sufficient dose to optical components to create permanent damage. Such damage will cause operational limitation that must be overcome to realize the potential of the 4th generation light sources that are in the planning process both in US and Germany. The liquid mirror provides the unique feature of renewing the optical surface in situ between successive intense light or x-ray pulses. Other applications include the using the renewable liquid mirror as an element of optical diagnostics in high-energy-density experiments, like the National Ignition Facility at Lawrence Livermore National Laboratory, Z facility at Sandia, and others, where these mirrors could be placed much closer to the point of the energy release than conventional solid-state mirrors. Systems where damage to the optical elements is a serious design constraint, include also rep-rate lasers for commercial applications.

[0013]   Referring again to FIG. 1, the liquid film 13 is formed by pressing a working liquid 11 through a porous substrate 12 by a piston 15. The working liquid 11 shown in FIG. 1 is mercury. In other embodiments of the invention the working fluid is composed of other materials that provide reflectivity. The working fluid in other embodiments can be conducting liquids including Gallium; NaK alloy (40 to 90% of K). The working fluid in other embodiments can be dielectric liquids including various alcohols, from ethyl alcohol C_2H_6O to benzyl alcohol C_7H_8O; glycerin; heavy hydrocarbons, like C_9H_{20}.

[0014]   The piston 15 moves within a cylinder 14. Before the gravitational instability has developed, the piston 15 sucks the liquid 13 back, and the cycle repeats. In the embodiment shown, the substrate 12 is made of fused capillaries of the same radius r_{cap}. In other embodiments, different porous substrates 12 can be used. In other embodiments, the system operates to push and pull the liquid not by a piston, but by a flexible membrane driven by actuators situated behind it.

[0015]   The embodiment illustrated in FIG. 1 presents a new class of centimeter-size renewable optical elements consisting in most cases of thin liquid films over porous substrates, which can be used in a rep-rate mode. Between two successive pulses the optical elements can be created anew. The film thickness of the system 10 is in the range from a few microns to a hundred of microns. The film behavior is strongly affected by capillary forces. Electrostatic, j×B, and capillary forces are used to control the shape of the surface of the film 13. Optical

elements, in most cases, can be arbitrarily oriented with respect to the gravitational force. The acronym "CAMEL" - - CApillary-Magneto-ELectrostatic"is used to designate this new class of optics.

[0016]   The word "capillary" as used herein in two senses. First, it is used as a noun, to designate a thin channel in a solid material. Second, following a long tradition, it is used as an adjective, to designate short-wavelength perturbations on the free surface of the liquid ("capillary waves"). The restoring force for this type of waves is provided by surface tension sometimes called a "capillary force," whence the "capillary waves."

[0017]   Renewing an optical element after each pulse has particular utility in developing optics for the fourth-generation light sources, such as LCLS and XFEL, where extremely intense beams of 8-10 keV photons will be generated. In the LCLS facility, for example, the flux of the 8-keV photons will be up to $1.4 \cdot 10^{14}$ W/cm^2 within a 250 fs pulse, with total fluence during the pulse reaching 40 J/cm^2. Such fluences may cause a serious damage to materials that can be used as mirrors, lenses, diffraction gratings, and other optical elements. The pulses will follow at a frequency ~ 100 Hz. Therefore, if these high-fluence beams are used without their preliminary significant attenuation, it is necessary to come up with some concept that will allow replacing optical elements after each pulse. In our approach, these elements are created anew after each pulse, on the surface of a liquid, without causing any damage to permanent structures.

[0018]   The CAMEL optics provide qualitatively new and important

features and can become the enabling technology for a broad variety of

applications, many of which are difficult to foresee at this time. Some of the

CAMEL optics applications include:

1) Renewable X-ray optics for ultra-intense x-ray free electron lasers (the

needs of LCLS initially stimulated us to consider pulse-to-pulse

renewable capillary diffraction gratings and gave rise to the first steps

in the analysis of the CAMEL concept);

2) Renewable optics for pulsed and rep-rate high-power lasers at longer

wavelengths, including the visible and infrared range.

3) Configurations used to create adaptive optics for steady-state low-

intensity sources.

[0019]   CAMEL optics for rep-rate applications allows one to monitor and

change the parameters of the optical system between two successive pulses at a

frequency of ~ 100 Hz.

[0020]   Engineering equations required for design of the CAMEL optics are

provided below.

Basic Notations Used In Description

[0021]   In the general equations we use the CGS system of units. In "practical"

estimates we use mixed units specified in each case.

a - distance of the conducting ring from the film surface
b - thickness of the substrate
c - speed of light

g – gravitational acceleration

h – thickness of a liquid film

k – wave number of perturbations

k^* - critical wave number (Equation (2.2))

r_{cap} – inner radius of the capillary

B – magnetic field strength

C_p – thermal capacity per unit volume

D_m – magnetic diffusivity

E – (1) electric field strength, and (2) Young's modulus for the substrate

R – (1) radius of a mirror, and (2) radius of an electrically charged ring

S - sound speed

U – voltage applied between the conducting ring and working liquid

α - capillary constant

β – volumetric thermal expansion coefficient

Δb – deformation of the substrate

Δh – (1) variation of the film thickness, and (2) thickness of the film layer heated by the laser

κ_B – Boltzmann constant

η - filling factor of the substrate (a fraction of the surface occupied by capillary holes)

λ – spatial period of the diffraction grating

λ_x – wavelength of x-ray radiation (or, generally, of the incident light)

ν - kinematic viscosity

ξ - displacement of a liquid element in the perturbation

ρ - liquid density

σ - electrical conductivity

τ - viscous dissipation time (Equation (8))

χ - thermal diffusivity

ω - frequency of surface waves

ω_{vibr} – frequency of vibrations of mechanical structure

[0022]   Although there exists a large variety of liquids suitable for the CAMEL optics, the numerical estimates set out herein only apply to one liquid, namely mercury. Parameters of the mercury required for discussion are listed in Table 1. In cases where we discuss dielectric liquids we assume that their dielectric constant is not much greater than 1, ε-1~1.

Table 1. Room Temperature Parameters for Mercury

Density	$\rho = 13.6 \text{ g/cm}^3$
Kinematic viscosity	$\nu = 1.2 \times 10^{-3} \text{ cm}^2/\text{s}$
Electrical conductivity	$\sigma = 1 \times 10^{16} \text{ s}^{-1}$
Magnetic diffusivity	$D_m = 3.5 \times 10^3 \text{ cm}^2/\text{s}$
Thermal diffusivity	$\chi = 2.7 \times 10^{-2} \text{ cm}^2/\text{s}$
Surface tension	$\alpha = 500 \text{ erg/cm}^2$
Thermal capacity	$c_p = 1.9 \times 10^7 \text{ erg/cm}^3\text{K}$
Sound speed	$S = 1.5 \times 10^5 \text{ cm/s}$
Volumetric thermal expansion coefficient	$\beta = 1.8 \times 10^{-4} \text{ K}^{-1}$

PROPERTIES OF CAPILLARY WAVES

[0023]   Numerous studies on the theory of capillary waves exist. For the purpose of this application, however, a somewhat "non-traditional" slice of this theory, which cannot be found in one single publication, is needed. Therefore, this section is included. In all the numerical examples we will consider the mercury.

Ideal Liquid

[0024]   Referring now to FIG. 2 a layer of a liquid 20 resting on a planar underlying surface 21 is shown. The substrate 21 is shaded. The surface of the film 20 is rippled at a wavelength λ $\lambda = 2\pi/k$. Dashed line 22 represents unperturbed surface of the film 20; δh is the amplitude of the surface perturbation.

[0025]   The dispersion relation for a small-amplitude wave propagating over this surface is:

$$\omega^2 = \left(kg + \frac{\alpha k^3}{\rho} \right) \tanh(kh) \qquad \text{(Equation 1)}$$

[0026] The first term in the bracket in Equation 1 describes a contribution of gravity to the restoring force; the second term describes the contribution of surface tension. These two terms become equal at $k=k^*$, where

$$k^* = \sqrt{\frac{g\rho}{\alpha}} \qquad \text{(Equation 2)}$$

For mercury, this critical wave number is $k^* \approx 5 \text{ cm}^{-1}$ and corresponds to the wavelength of 1.2 cm.

[0027] FIGS. 3 and 4 show dispersion properties of surface waves in the setting of FIG.1. FIG. 3 shows dispersion curves for the mercury; curves, from the lower to the upper one, correspond to film thickness of 3 µm, 30 µm, and 100 µm, respectively; the dots show the points where the condition $\omega\tau=1$ is satisfied, where τ is defined by equation 8; to the lhs of the dots, the waves are strongly damped with the damping rate defined by equation 9. Dashed vertical line is the line where $k=k^*$.

[0028] FIG. 4 depicts dispersion relation for an arbitrary fluid presented in the dimensionless form, with ω measured in units of $(h/g)^{1/2}$, and k measured in units of $1/h$ ($\tilde{\omega} = \omega\sqrt{h/g}$, $\tilde{k} = kh$). In these units the dispersion relation (1) reads:

$$\tilde{\omega}^2 = \tilde{k}\left[1 + \frac{\tilde{k}^2}{(k^*h)^2}\right]\tanh\tilde{k} \qquad \text{(Equation 1')}$$

Curves from the lower to the upper, correspond to the parameter k^*h equal to 10^1, 10^2, and 10^3 respectively.

[0029]   For short wavelengths, $kh>1$, the perturbation is localized near the free surface, and decays exponentially with the distance from the surface, with the e-folding length being $1/k$. The dispersion relation for such perturbations reads as:

$$\omega^2 = \left(kg + \frac{\alpha k^3}{\rho} \right) \qquad \text{(Equation 3)}$$

For these short waves, parallel and perpendicular (to the surface) displacements of liquid elements are of the same order of magnitude.

[0030]   Long-wavelength perturbations, with $kh<1$, occupy the whole layer. The parallel to the surface displacements of liquid elements ($\xi_{||}$) are in this case much greater than perpendicular displacements (ξ_z). These displacements are:

$$\xi_z = z\frac{\delta h}{h}\cos(kx - \omega t); \xi_{||} = \frac{\delta h}{kh}\sin(kx - \omega t), \qquad \text{(Equation 4)}$$

where δh is the amplitude of the vertical displacement of the surface. The parallel component is independent of z (up to higher-order corrections in the parameter kh). As is clear from Equation (4), $\xi_{||} \sim \delta h/kh >> \delta h$. The dispersion relation for long-wavelength ($kh<1$) perturbations is

$$\omega^2 = \left(kg + \frac{\alpha k^3}{\rho} \right)kh \qquad \text{(Equation 5)}$$

[0031]   The dispersion relation (1) describes also gravitational instability of the liquid film turned "upside down" so that the substrate is now at the top. Dispersion relation in this case can be formally obtained from (1) by reversing the sign of g,

$$\omega^2 = \left(-kg + \frac{\alpha k^3}{\rho}\right)\tanh(kh) \qquad \text{(Equation 6)}$$

Perturbations are stable (ω real) for short-enough wavelengths, $k>k^*$, and unstable otherwise.

[0032] Compressibility of the liquid is unimportant, because the phase velocity is typically much smaller than the sound velocity S. Indeed, for the mercury the phase velocity, $\sqrt{\alpha k/\rho}$, becomes formally greater than S only for unrealistically large k, $k>5\cdot10^8$ cm^{-1}.

Viscous Effects

[0033] Viscosity causes damping of stable perturbations. It cannot stabilize unstable perturbations with ($k<k^*$) in the case of inverted geometry but, in some cases, can reduce their growth rate.

[0034] In the case of short wavelengths, $kh>1$, the damping rate Imω is equal to:

$$\text{Im}\,\omega = -2\nu k^2 \qquad \text{(Equation 7)}$$

For long wavelengths, $kh<1$, the damping rate depends on the parameter $\omega\tau$, where τ is a characteristic time for viscous shear flow to propagate over the film thickness h,

$$\tau \equiv \frac{h^2}{\nu} \qquad \text{(Equation 8)}$$

For a mercury film with $h=25$ •m, one has $\tau=5.2\cdot10^{-3}$ s.

[0035] We will need the damping rate only for the case of small $\omega\tau$. In this domain, perturbations become essentially aperiodic, with Imω>>Reω, and

$$\text{Im}\,\omega \approx -\frac{h^3 k^2}{3\nu}\left(g + \frac{\alpha}{\rho}k^2\right) \qquad \text{(Equation 9)}$$

For the inverted configuration, and wavelengths with $k<k^*$, the system is

unstable, with the growth rate being

$$\text{Im}\,\omega = \frac{h^3 k^2 g}{3\nu}\left(g - \frac{\alpha}{\rho}k^2\right) \qquad \text{(Equation 10)}$$

CREATING A LIQUID FILM BY PRESSING A LIQUID THROUGH A POROUS SUBSTRATE

General Approach

[0036] Referring to FIG. 1, the use of wettable and non-wettable substrates 12

is possible. The use of a non-wettable substrate would probably allow a complete

removal of the liquid from the outer side of the system during the "in" move of

the piston. A mechanical barrier (a rim) of the height approximately equal to the

film thickness could be used to prevent the film from spreading laterally. For

non-wettable substrate, the pressure in the liquid will be non-negative, so that

there will be no concern about cavitation. A wettable substrate (with a non-

wettable rim) is also conceivable. However, for the wettable substrate, one can

expect that droplets will stick to the areas between the holes of the capillaries and

the liquid will not be completely removed from the surface after every pulse.

During the "in" motion of the piston, a negative pressure will develop, thereby

creating a possibility of cavitation. On the other hand, the droplets will be

absorbed by the liquid during the next pulse, and flat surface will be formed

again; also, the negative pressures developing during the "in" move are small

and shouldn't lead to cavitaiton in a liquid of a normal purity. And, the

wettable substrate would allow production of thinner films, with a thickness less

than the size of capillaries.

[0037]   Referring again to FIG. 1 one cycle of the motion of the piston will be

described. Starting from the position where the liquid film 13 is present on the

outer surface of the porous substrate 12. The piston 15 begins moving away from

the substrate 12 and, by the end of a half-cycle, "sucks" the liquid 11 out of the

capillaries into the volume behind the substrate 12. On the reverse motion, the

piston 15 presses the liquid 11 through the capillaries and creates a liquid film 13

with a high-quality reflecting surface. The stroke of the piston 15 is equal to the

thickness b of the substrate (plus the film thickness, which is usually negligible

compared to b). It may suffice to have a stroke as small as a few thicknesses (h) of

the liquid film. We, however, will discuss a more difficult in realization case of a

larger stroke. This larger stroke may be necessary if one wants to extract all the

working liquid from the capillaries during every cycle. A continuing lateral flow

of the working liquid through a plenum behind the substrate could then be

organized to gradually refresh it. A cleaning system can be introduced in this

contour.

[0038]   In one embodiment it is a porous unit. In another embodiment it is a

porous substrate. In another embodiment it is a capillary substrate. In another

embodiment it is planar. In another embodiment it is contoured. In another

embodiment it is a figured porous substrate. In another embodiment it comprises

holes extending through said penetrable unit. In another embodiment it the holes

are capillary size holes.

Deformations of the Substrate

[0039]   In order to provide a smoothest possible surface of the mirror, the

radius of capillaries, r_{cap}, must be made as small as possible. On the other hand,

the pressure required to push the liquid through capillaries, Δp, increases as $1/r_{cap}$:

$$|\Delta p| = \frac{2\alpha}{r_{cap}} . \qquad \text{(Equation 11)}$$

For wettable materials one would have to apply a negative Δp to suck the liquid

out of the capillary. When making the estimate (11), we considered perfectly

non-wettable or perfectly wettable material, with the contact angle being either

180° or 0°. The pressure Δp applied to the substrate causes its deformation, which

we will evaluate in this sub-section.

[0040]   For the mercury,

$$\Delta p(atm) \approx \frac{10}{r_{cap}(\mu m)} . \qquad \text{(Equation 12)}$$

It is desirable not to make Δp too large, to avoid too strong deformation of the

substrate; this pushes us in the direction of the larger radii r_{cap}. For the numerical

example we choose r_{cap} =5 μm. According to Equation 11, this corresponds to the

pressure of 2 atm.

[0041]   Returning to the issue of the cavitation touched upon the previous section, one can also note that the ram pressure generated in the liquid, ρv^2, is small compared to the capillary pressure (12) and cannot contribute to the cavitation. Indeed, the maximum liquid velocity is $\sim 2\pi b/t_{piston}$ and, in for the aforementioned set of the numerical parameters is ~ 60 cm/s, yielding the maximum ram pressure of a mere 0.04 atm.

[0042]   The maximum displacement Δb of the substrate occurs in its center. Displacement amplitude is:

$$\Delta b = \frac{3(1-\mu^2)R^4 \Delta p}{16 b^3 E}, \qquad \text{(Equation 13)}$$

where R is the mirror radius, E is the Young's modulus, and μ is the Poisson coefficient of the substrate. To make an upper-bound estimate of Δb, we assume that E is 10 times less than the Young's modulus for the steel, i.e., we take $E=2\cdot10^{10}$ n/m^2. With regard to μ, we take a value of 0.3, typical for many materials. Assuming, as before, that $R=0.5$ cm, and $b=0.1$ cm, we find that $\Delta b \sim 1$ μm, the value that looks acceptable.

[0043]   The characteristic frequency of the lowest mode of elastic vibrations of the substrate is :

$$\omega \sim \sqrt{\frac{b^2 E}{R^4 \rho}}, \qquad \text{(Equation 14)}$$

[0044]   where ρ is the substrate density. Taking $\rho=2$ g/cm^3, and the other parameters as before, one finds that the resonant frequency is $\sim 10^5$ s^{-1}. The

presence of a heavy underlying liquid reduces this frequency by a factor of a few,

leaving it still orders of magnitude higher than the frequency of the piston

motion. This justifies using a steady-state approximation in evaluating Δb.

[0045]   Rough estimates of displacement and of the lowest eigenfrequency for

a rectangular membrane can be obtained by replacing R in Equations 13 and 14

by $\left(2L_1^{-2} + 2L_2^{-2}\right)^{-1/2}$, where L_1 and L_2 are the lengths of the sides of the rectangle.

[0046]   An additional force on the membrane will appear because of the

viscous friction of the working liquid against the walls of the capillaries. It is

assumed that liquid inside capillaries performs a vertical sinusoidal motion with

the period t_{piston} and the amplitude $b/2$ (the distance between the upper and the

lower position of the surface is then equal to the thickness of the substrate). This

motion is driven by the piston. The amplitude of the viscous friction force

between the walls and the liquid can be estimated as $2\pi^2 b^2 v\rho / t_{piston}$. The number

of capillaries per unit surface area of the substrate is $\eta / \pi r_{cap}^2$, where η (~1) is a

filling factor by which we mean the ratio of the area occupied by the holes to the

total area of the substrate. Multiplying the two quantities, one finds additional

pressure required to press the liquid through capillaries:

$$\Delta p_{visc} = \frac{2\pi\eta b^2 v\rho}{r_{cap}^2 t_{pist}}.$$

(Equation 15)

For mercury, and $\eta=0.5$, $r_{cap}=5$ μm, $b= 1$mm, and $t_{pist}=0.01$s one finds that

Δp_{visc}~0.35 atm and can be neglected compared to the pressure perturbation (12).

[0047] Two caveats are in order here. First, the real motion of the piston will probably be not a pure sinusoid. It might be worth adding a "plateau" on the dependence of the piston position vs time around the point where the thickness of the liquid film has reached a desired value. This would eliminate any unnecessary motions that could distort the surface of the film around the time when the optical pulse arrives. For the period of 0.01 s this plateau could probably be 0.002 s long. However, the presence of this relatively short plateau will have no significant effect on the estimate of the force (15). The second caveat is related to the fact that, when making estimate (15), it is implicitly assumed that the liquid flow in the capillary is a pure Poiseuille flow. In fact, the presence of the free surface of the liquid leads to a more complex 2D flow near the surface. We neglect this subtlety in our estimates because of a very large b/r_{cap} ratio.

The Waviness of the Reflecting Surface

[0048] The substrate is made of many capillaries closely packed together. It is assumed that the walls of the capillaries have a thickness of the order of r_{cap} ($\eta \sim 1$), the spatial scale of the surface structures can be estimated as r_{cap}. When the liquid is pressed through the capillaries, its surface gets rippled at this scale or, in other words, the ripples have a characteristic wave number $k \sim 1/r_{cap}$. These ripples experience a rapid viscous damping described by Equation. (7). For mercury and $r_{cap} = 5$ microns one has $\mathrm{Im}\,\omega \sim 10^4$ s^{-1}; in other words, these perturbations damp away during a small fraction of the in-out period. Generally speaking, initial perturbations will have a broad spectrum where also longer wavelengths will be

present. Specific details of the spectrum will be determined by possible larger-scale correlations between positions of individual capillaries. These correlations will depend on the manufacturing process and are unknown to us at this stage. One can only say that even perturbations with spatial scales $\sim 10 r_{cap}$ decay relatively quickly, within $\sim 10^{-2}$ s.

[0049]   A special class is formed by long-wave perturbations with $k < k^*$, which are unstable for the upside-down orientation. The finite radius of the mirror limits wave number of perturbations from below, by the value approximately equal to

$$k_{min} = 1.5/R \qquad \text{(Equation 16)}$$

(the exact numerical coefficient depends on the boundary conditions on the rim). For mercury, and $R = 0.5$ cm, the unstable mode is indeed present ($k_{min} < k^*$). However, it grows very slowly because of the viscous effects. Indeed, Equation (10) shows that for a 25 μm thick mercury film, and $k = 3$ cm^{-1}, the growth rate is $6 \cdot 10^{-2}$ s^{-1}. The corresponding e-folding time is 15s, much longer than the period of the piston motion. For a rectangular mirror with the lengths of the sides equal to L_1 and L_2, under the assumption that displacement is zero on the boundaries, the minimum wave number is

$$k_{min} = \pi \sqrt{\frac{1}{L_1^2} + \frac{1}{L_2^2}} \qquad \text{(Equation 17)}$$

[0050]   Although the instability by itself is not a big problem (because of its small growth rate), the absence of the restoring force for the perturbations with

$k<k^*$ means that at the large scales the film must be perfect during the whole time of its creation, with tilts or bumps with a scale $k<k^*$ being inadmissible. This means that the properties of the porous substrate must be uniform to a high level of precision at these scales.

[0051]   As the long-wavelength instability is so slow, it is not a limiting factor in the increase of the size of the mirror. The uniformity of the substrate at larger scales may pose more serious problems.

[0052]   Conversely, if one wants to have a mirror that would be stable for all perturbations, and whose surface would experience restoring forces bringing the surface to an equilibrium shape (thereby relaxing requirements to the quality of the substrate), one might want to reduce its radius R to the values below, roughly speaking, $1.5/k^*$ (3 mm for mercury). The problem is that the equilibrium shape for a small mirror will not be planar, but will be a meniscus. Referring now to FIG. 5, the making of a quasiplanar mirror in this case by introducing correcting electrostatic forces is illustrated. A quasiplanar mirror is formed near the center of the meniscus. An electric field is created between the correcting electrode 41 and the liquid mirror 43. The solid line 43 depicts initial surface of the meniscus; dashed line 44 shows a corrected surface, after the voltage is applied; this corrected surface 44 is nearly planar near the axis. A supporting structure 42 supports the liquid. A supporting structure 42 operatively retains the liquid 44. The supporting structure 44 may comprise a penetrable unit. The minimum possible level of deviations of the mirror surface

from planarity in the stable domain is determined by thermal fluctuations. The spectral energy density W_k of thermal fluctuations is defined by the equation:

$$dW = W_k dk_x dk_y \qquad \text{(Equation 18)}$$

where dW is the energy of surface oscillations in the interval of wave numbers dk_x, dk_y per unit surface area of the plane. For thermal fluctuations, one has

$$W_k = \frac{\kappa_B T}{(2\pi)^2} \qquad \text{(Equation 19)}$$

(the Rayleigh-Jeans distribution, with T and k_B being the temperature of the film and the Boltzmann constant, respectively). On the other hand, W_k is related to the spectral density of surface displacements $(\xi^2)_k$ via equation:

$$W_k = \frac{\left(\xi^2\right)_k \omega_k^2 \rho}{k} \cdot \frac{\sinh(2kh)}{\cosh(2kh) - 1} = \left(\xi^2\right)_k \left(\rho g + \alpha k^2\right) \qquad \text{(Equation 20)}$$

(we have used dispersion relation (1)). Equations (19)-(20) then yield the following expression for the contribution $d\bullet^\bullet$ of the interval dk_x, dk_y to the mean-square deviation of the surface from the plane:

$$d\xi^2 \equiv \left(\xi^2\right)_k dk_x dk_y = \frac{\kappa_B T}{(2\pi)^2 \left(\rho g + \alpha k^2\right)} \cdot dk_x dk_y \qquad \text{(Equation 21)}$$

Remarkably, this result coincides with the previously derived expression for $d\xi^2$ for the liquid of an infinite depth. For capillary waves (i.e., the waves with $k > k^*$, Equation (2)), one obtains:

$$d\xi^2 \equiv \frac{\kappa_B T dk}{2\pi k \alpha} \qquad \text{(Equation 22)}$$

We have taken into account that $dk_x dk_y = 2\pi k dk$. The contribution to the surface

roughness from the wave numbers whose absolute values lie between k_1 and k_2 is:

$$\xi^2(k_1 < k < k_2) = \frac{\kappa_B T}{2\pi\alpha} \ln\left(\frac{k_2}{k_1}\right)$$
(Equation 23)

The longer wavelengths, $k < k^*$, give smaller contribution. One sees that for a rough

estimate of the r.m.s. value for deviations from planarity one can use an equation

$$\sqrt{\langle \xi_\varsigma^2 \rangle} \approx \sqrt{\frac{5\kappa_B T}{2\pi\alpha}}$$
(Equation 24)

where we have replaced the logarithmic factor by its typical numerical value ~ 5. For

mercury at the temperature ~300 °K, one has $\sqrt{\langle \xi^2 \rangle}$ ~1 Å. This determines the

minimum possible surface roughness. The actual roughness may be somewhat

larger than (24) because of the finite size of atoms (or molecules) forming the liquid.

The Role of Vibrations

[0053]   High-precision optical elements installed on an experimental facility

usually experience some level of vibrations originating from external sources.

There is an issue of possible misalignment caused by these vibrations. For the

optical systems a great experience has been accumulated in dealing with this

problem. In this sense, solid elements of the system discussed above (e.g.,

substrates) do not create any specific new problems. A question may arise,

though, on how vibrations could affect liquid surfaces.

[0054]   Typical frequencies of vibrations, ω_{vibr}, lie in the range below 300 s^{-1}.

They are below the eigenfrequencies of the substrate (Equation 24)). We therefore

assume that the substrate moves as a perfectly rigid body. This motion can be

represented as a superposition of translational motion and tilts.

[0055]   Translations are first considered. They are characterize by a

displacement vector $\xi(t)$. The translational acceleration $d^2\xi/dt^2$ can be represented

as a sum of the tangential and normal acceleration. The normal acceleration does

not change the shape of a planar surface of the mirror. So, they are considered

tangential acceleration. It causes a liquid flow along the surface of the mirror and

leads thereby to tilting of the liquid surface. For relatively low frequencies

mentioned above and thin-enough films, the condition $\omega_{vibr}\tau\!<\!1$ holds (where τ is

defined as in (8)), meaning that the tangential velocity is a linear function of the

distance from the substrate surface (Couette flow), with the average (over the

film thickness) velocity equal to

$$\overline{v} = \frac{\tau\ddot{\xi}_t}{2},$$ (Equation 25)

where by ξ_t it is meant only tangential component of the displacement. This flow

causes increase of the depth on one side of the mirror and decrease on the other

side. The estimate for the relative displacement Δh of the liquid surface at two

opposite sides of the disk then follows,

$$\Delta h \sim \frac{h\omega_{vibr}^2\xi\tau}{R}\min(\omega_{vibr}^{-1},\Delta t)$$ (Equation 26)

where Δt is a time interval during which thin film exists at the outer surface of the substrate (0.03 s in the example given). It was deliberately overestimated Δh by writing ξ instead of ξ_t.

[0056]   The tilt of the surface of the film relative to the substrate is $\Delta h/R$. In order to be unimportant, it must be less than the tilt of the substrate itself, θ. The latter is related to the displacement by $\theta \sim \xi/L$, where L is the size of the structural element of the facility to which the mirror system is attached, or the wavelength of vibrations in this element, if the latter is shorter. In this way it is possible to arrive at the following criterion for unimportance of specifically "liquid" effects in vibrations:

$$\frac{hL\omega_{\mathrm{vibr}}^2 \tau}{R^2} \min(\omega_{\mathrm{vibr}}^{-1}, \Delta t) < 1 \quad \text{(Equation 27)}$$

As already mentioned, for thin-enough films, one has $\omega_{\mathrm{vibr}}\tau < 1$. This means that condition (27) is certainly satisfied if $hL<R^2$; for our standard set of parameters, $R=0.5$ cm, $h=25$ microns, this latter inequality holds if $L<100$ cm.

[0057]   The normal component of the acceleration does not affect the planar surface of the liquid film but it may affect the curved surface of the type we discuss in the next section. It is also worth noting that tilts of the substrate cause smaller tilt of the liquid surface relative to substrate than tangential accelerations we have just discussed.

Maximum Intensity of the Laser Pulse

[0058]   There are two limitations on the intensity of the laser pulse that can

still be handled by the system without damaging its permanent components. The

first is decrease of the reflectivity during the laser pulse itself (because of, e.g.,

bringing the surface to a boil temperature during the pulse). The second is

possible damage to the substrate by mechanical and thermal perturbations

initially produced near the surface of the liquid and then propagating towards

the substrate. The first constraint is not specific to the concept. There exist

numerous studies of that issue. Therefore only the second constraint is discussed,

limited to a qualitative discussion. Consider a 1-dimensional problem, assuming

that the spot size on the surface of the film is greater than the film thickness.

[0059]   There are two characteristic times important in the problem, the sound

propagation time through the film, h/S (where S is the sound velocity), and the

time of a thermal diffusion, h^2/χ (where χ is thermal diffusivity). For a 25 μm-

thick mercury film, the acoustic time is ~ $2 \cdot 10^{-8}$ s, and the thermal conduction

time is ~$2 \cdot 10^{-4}$ s.

[0060]   The characteristic pulse-width of the x-ray pulse in the LCLS project is

in the range of 200-300 fs. As the laser pulse is shorter than the acoustic time, the

pressure perturbation created near the surface, propagates as an acoustic pulse

(which may become a shock wave, if the amplitude is large enough). The energy

deposition occurs at a depth Δh ~ 0.3 μm in mercury (this is determined by

photo-absorption of x rays and subsequent energy transport by keV-range

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electrons). The liquid within this layer is heated up to some temperature ΔT

virtually instantaneously (compared both to the sound propagation time and the

heat conduction time over Δh). The resulting pressure perturbation Δp_0 then

drives an acoustic pulse propagating towards the substrate. It may form a weak

shock by the familiar overtaking process. The shock is formed if the condition

$$\Delta p_0 > \rho S^2 \frac{\Delta h}{h} \qquad \text{(Equation 28)}$$

holds. By noting that the pressure perturbation in the isochoric heating can be

evaluated as

$$\Delta p_0 \sim \rho S^2 \beta \Delta T \qquad \text{(Equation 29)}$$

(where μ is volumetric thermal expansion coefficient), one finds that the shock is

formed if

$$\Delta T > \frac{\Delta h}{\beta h} \qquad \text{(Equation 30)}$$

For mercury in the aforementioned example, the shock is formed if $\Delta T > 50$ K.

This corresponds to the deposited energy $C_p \Delta h \Delta T > 3$ mJ/cm^2.

[0061]   If the shock is indeed formed, it weakens during its propagation

through the film [9]; the pressure jump at the distance h from the surface

decreases to $\Delta p \sim \Delta p_0 \sqrt{(\rho S^2 / \Delta p_0)(\Delta h / h)} < \Delta p_0$, the last inequality being a

consequence of (28). For the energy deposition in the range of the critical value of

3 mJ/cm^2, the expected pressure amplitude will be in the range of 3 Kbar,

somewhat below the yield strength of good structural materials.

[0062] For longer-pulse, higher energy-per-pulse lasers, the favorable regimes of operation are those where the pulse width is larger than the sound propagation time h/S, so that thermal stresses in the heated surface layers increase adiabatically slowly, and do not lead to shock formation. They just cause a quasi-equilibrium thermal expansion of the heated layer, with only small pressure increase in the bulk of the film. If the pulse is shorter than h/S, it is at least desirable to make it longer than $\Delta h/S$. The pressure perturbation in the pressure pulse that will be propagating towards the substrate will then be much less than Equation 29).

ELECTROSTATICALLY CONTROLLED MIRRORS

Mirror Focal Length

[0063] FIG. 6 illustrates creating a focusing mirror by introducing an electrostatic field between the liquid and the ring. In other embodiments more sophisticated sets of electrodes can be used, including electrodes segmented in the azimuthal direction. As shown in FIG. 6, another CAMEL configuration generally designated by the reference numeral 50, is a parabolic mirror 51 in a thin layer of a liquid 52, with a substrate 53 being a flat porous conducting plate. A ring electrode 54 of a radius R will be situated at some distance $(\sim R)$ over the surface 51. Electric field will distort the surface of the liquid, with the region near the axis forming a parabolic mirror. If a thin ring is situated at a distance a from the surface of the plate, the electric field at the planar surface of the conducting liquid (kept at the ground potential) is determined by the equation

$$E_z(r) = \frac{2URa}{\Lambda} \int_0^\pi \frac{d\varphi}{\left(a^2 + R^2 - 2Rr\cos\varphi + r^2\right)^{3/2}} \qquad \text{(Equation 31)}$$

where U is the ring potential, and Λ is a logarithmic factor depending on the

(small) thickness d of the ring $\{\Lambda \approx \ln[2\min(a, R)/d]\}$; r is the distance from the axis

of symmetry. Under the action of a ponderomotive force, the surface becomes

perturbed. However, these perturbations are small (at least for the mirrors with

the focal distance much greater than the mirror radius). We will neglect these

small corrections when evaluating E_z. If there is a need to refresh the liquid

between the two subsequent pulses, one can use a conducting, porous substrate.

[0064]   For large-focal-length mirrors deviations of the surface from planarity

are small, $\Delta h \ll R$, and one can use the linear equation to find Δh :

$$\frac{\alpha}{r}\frac{d}{dr}r\frac{d\Delta h}{dr} = \rho g\Delta h - \frac{E_z^2}{8\pi} \qquad \text{(Equation 32)}$$

We will study its solution near the axis, at small r. In this zone the

ponderomotive force can be presented as an expansion:

$$\frac{E_z^2}{8\pi} = \frac{\pi(Ua)^2}{2\Lambda^2\left(a^2 + R^2\right)^3}\left[1 + C_1\left(\frac{r}{R}\right)^2 + C_2\left(\frac{r}{R}\right)^4 + \ldots\right] \qquad \text{(Equation 33)}$$

We limit ourselves to the first three members. One has:

$$C_1 = \frac{3R^2\left(3R^2 - 2a^2\right)}{2\left(a^2 + R^2\right)^2}; C_2 = \frac{3R^4\left(4a^4 - 17a^2R^2 - \frac{329}{64}R^4\right)}{2\left(a^2 + R^2\right)^4} \qquad \text{(Equation 34)}$$

If we are interested in not-too-small mirrors, with the size exceeding $1/k^*$, one

can neglect capillary forces and set the left hand side (l.h.s.) of Equation 32 to

zero. Then one obtains the following expression for the function $\Delta h(r)$:

$$\Delta h(r) = \frac{\pi(Ua)^2}{2\rho g \Lambda^2 \left(a^2 + R^2\right)^3}\left[1 + C_1\left(\frac{r}{R}\right)^2 + C_2\left(\frac{r}{R}\right)^4 + \ldots\right] \qquad \text{(Equation 35)}$$

If corrections related to the finite value of the capillary forces are required, one can find them by substituting this solution to the l.h.s. of Equation 32. The ideal parabolic mirror corresponds to all the terms beyond r^2 being equal to zero. The focal length in the paraxial domain, where the third and higher-order terms in the R.H.S. of (35) can be neglected, is

$$F = \frac{\rho g \Lambda^2 \left(a^2 + R^2\right)^5}{3\pi(Ua)^2 \left(3R^2 - 2a^2\right)} \qquad \text{(Equation 36)}$$

[0065]   At given voltage U and radius R of the ring, the focal length varies as a function of the distance a between the ring and the surface. Assuming that the ring thickness d is small, we neglect a weak logarithmic dependence of Λ vs a) At small a, the surface near the axis is almost flat, and the focal length is infinite. It reaches a minimum at the distance $a \approx 0.45R$. At the further increase of a, the surface near the axis again becomes flat (at $a=1.22R$), and then becomes convex, giving rise to a defocusing mirror. The minimum focal length for the defocusing mirror is attained at $a \approx 1.57R$. Finally, at even larger a's, the surface again flattens.

[0066]   At the distance $a \approx 0.45R$ corresponding to the minimum focal length, one has

$$F = F_0 \equiv \frac{0.51 \rho g \Lambda^2 R^6}{U^2} \qquad \text{(Equation 37)}$$

Equation 37 shows that, with mercury as the working liquid, creating a mirror

with a focal length of 50 cm by a ring of the radius $R=0.5$ cm requires a modest

voltage ~ 1.5 kV (we assumed •=3). With this voltage, the maximum value of Δh

(which is reached just under the ring, at $r \approx R$) is approximately 30 μm. This sets

the minimum value of the initial thickness of the liquid film, which must be

greater than ~ 30 μm. Note that a voltage of 1.5 keV over a gap of ~ 0.5 cm will

not cause a breakdown even for an electrode without special surface treatment.

[0067]   One advantage of this scheme is that it works not only for conducting

but also for dielectric liquid (for the latter, the result analogous to Equation 4.5

will also depend on the dielectric constant). Another advantage is related to a

possibility of using several ring electrodes segmented in the azimuthal direction,

each with an independent voltage control. By proper adjustment of the voltages

applied to azimuthal segments, on can create an approximately parabolic mirror

with an axis tilted with respect to the normal to the surface. This demonstrates

one outstanding feature of the CAMEL concept: remote control of the focal

length and optical axis of a figured mirror, without introducing any

mechanically moving parts.

[0068]   In the aforementioned embodiment, the electrode in front of the mirror

limits the solid angle that can be used for collecting light. For dielectric liquids,

one can eliminate this constraint by using a ring situated below the liquid film

and dielectric substrate. This additional embodiment of a system incorporating

the present invention is illustrated in FIG. 7 wherein a ring 61 is situated below

the liquid film 62 and dielectric substrate 63. Liquid dielectric with a dielectric

constant ε_1 is situated above the substrate 63 with a dielectric constant ε_2. The

unperturbed surface of the liquid is shown by a dashed line 64. After voltage is

applied to a ring electrode 61 of a radius R, the surface becomes distorted and,

near the axis, acquires the shape of a focusing mirror. The second electrode is

situated far from the ring.

<u>Characteristic Time-Scales for Changing the Shape of the Mirror</u>

[0069]   Consider a pool of liquid of the thickness $h<<R$. If one wants to vary

the focal length and orientation of the optical axis by varying the voltages at

different electrodes, one has to evaluate the characteristic time $\tau_{response}$ within

which the liquid will redistribute itself over the surface of the substrate and settle

down in the new equilibrium. For thin films, viscous forces may be important

and could slow down the response time. Basically, this time is equal to the time

of viscous damping of surface waves with the wave-number $k\sim 1/R$. For not too

thick films, the damping rate is determined by Equation 9, with the 1st term

neglected (because we assume that $k^*R>1$) According to the estimate (9), we have

$$\tau_{response} \sim \frac{2\nu R^2}{h^3 g} \qquad \text{(Equation 38)}$$

For a mercury mirror with $R=0.5$ cm and $h=30$ μm, one finds $\tau_{response} \sim 20$ s.

According to Equation 38, the response is faster for thicker mirrors. At some

point, however, the response time evaluated according to Equation 38 becomes

shorter than the viscous time (8), and applicability conditions of Equation 9 (or,

equivalently, Equation 38) break down. The maximum thickness at which one can still use Equation 38 can be evaluated from the condition $\tau_{response} \sim \tau$ (with τ as in Equation 8), which yields:

$$h \sim \left(\frac{2v^2 R^2}{g} \right)^{1/5}$$

(Equation 39)

The corresponding response time is

$$\tau_{response} \sim \left(\frac{4R^4}{g^2 v} \right)^{1/5}$$

(Equation 40)

For the mercury mirror with R=0.5 cm, one has h=150 m, and the corresponding shortest response time ~0.2 s.

[0070]   For the film thicker than the one evaluated from Equation 39, the response will be accompanied by excitation of the wave motion of the liquid. One could significantly reduce the amplitude of transient waves by applying the voltage in an "adiabatically slow" fashion. How much one can gain then in terms of the response time, will be analyzed in further reports. Too thick films, on the other hand, may be too vulnerable to vibrations.

MAGNETICALLY CONTROLLED MIRRORS

[0071]   The j×B force can be used to prevent the liquid from sliding down along the surface of a tilted flat substrate. This may be required, if one needs to create a renewable quasi-steady-state planar mirror. The schematic of a liquid mirror in this case is shown in FIG. 8. The presence of a large permanent magnetic field B normal to the surface 71 allows one to reduce requirements to

the current that flows across this field, and thereby make the Joule heating of the film insignificant.

[0072]   The concept illustrated by FIG. 9 can be used to make a small renewable focusing (defocusing) mirror. Two concentric electrodes, electrode 81 and ring electrode 82, are introduced into the liquid film. The substrate 83 is in this case is dielectric and the substrate 83 is a porous substrate as previously described. The radial current flowing between the inner and outer electrodes, generates the azimuthal magnetic field. The j×B force arises which is directed upward and which causes a perturbation of the surface. The working part of the mirror surface will be situated near the axis, where one can create a profile close to a parabolic profile. The magnetic field strength required to produce a 30-μm variation of the thickness of the film in the mirror of 0.5 cm radius is modest, for the mercury it is ~ 30 G; this corresponds to a modest current ~ 100 A.

DESCRIPTION OF ADDITIONAL EMBODIMENTS

[0073]   Referring to FIG. 10, another embodiment of a system incorporating the present invention is illustrated. The system is generally designated by the reference numeral 140. The system 140 provides a planar renewable mirror. An actuator 141 is connected to a flexible membrane 142. The actuator 141 and flexible membrane 142 are carried by mechanical support 143. A liquid fills plenum 144. The reflecting liquid film 1 (5-50 gm thick) is formed by pressing the working fluid 144 through the porous substrate 145 by the actuator 141 and flexible membrane 142. Before the gravitational instability of the free surface of

the liquid has developed, the actuator 141 and flexible membrane 142 sucks the liquid back to the plenum, and the cycle repeats. Specific instability time is determined by the properties of the fluid and the thickness of the film. The free surface of the planar mirror will not suffer from deformations caused by this instability for the time intervals in the range from 0.01 to 0.1 s. The substrate should be --1 mm thick to assure sufficient stiffness against deformations caused by the motion of the liquid through it.

[0074] The working liquid shown in FIG. 10 is mercury. In another embodiment of the invention the working liquid is gallium. In other embodiments of the invention the working fluid is composed other materials that provide reflectivity. In other embodiments of the invention the working fluid is composed other materials that provide reflectivity. The working fluid in other embodiments can be conducting liquids including Gallium; NaK alloy (40 to 90% of K). The working fluid in other embodiments can be dielectric liquids including various alcohols, from ethyl alcohol $C_2 H_6 O$ to benzyl alcohol $C_7 H_8 O$; glycerin; heavy carbohydrates, like $C_9 H_{20}$.

[0075] Another embodiment of the system is shown in FIG. 11. The system is generally designated by the reference numeral 150. The system 150 provides a planar renewable mirror. A bellows 151 is held in place by stiff ring 153. A liquid fills plenum 152. One cycle of the motion of the system will be described. The bellows 151 begins moving the liquid out of the plenum 152. On the reverse motion,

the bellows 151 presses the liquid through the capillaries and creates a liquid film with a high-quality reflecting surface.

[0076]   A modification of this system is a mirror formed over a shaped substrate shown in FIG. 12, which illustrates formation of a curved mirror 164 in a "normal" orientation. The flow of liquid under the action of the gravity force is slow because of viscous friction. In some configurations, if necessary, this flow can be stopped altogether by applying a properly oriented jxB force.

[0077]   Referring again to FIG. 12, an embodiment of a system incorporating the present invention is illustrated. The system is generally designated by the reference numeral 160. The system 160 provides a contoured renewable mirror. A piston 161 moves the working liquid 162 within a mechanical support. A figured porous substrate 163 is located on the other side of the working liquid 162 from piston 161. In another embodiment the figured porous substrate comprises holes extending entirely through the penetrable unit. In another embodiment the holes are capillary size holes.

[0078]   One cycle of the motion of the piston 161 will be described starting from the position where the contoured film 164 is present on the outer surface of the figured porous substrate 163. The piston 161 begins moving the away from the substrate 1163 and, by the end of a half-cycle, "sucks" the liquid out of the capillaries behind the substrate 163. On the reverse motion, the piston 161 presses the liquid through the capillaries and creates a contoured liquid film reflecting system with a high-quality reflecting surface.

[0079]   While the invention may be susceptible to various modifications and

alternative forms, specific embodiments have been shown by way of example in

the drawings and have been described in detail herein. However, it should be

understood that the invention is not intended to be limited to the particular

forms disclosed. Rather, the invention is to cover all modifications, equivalents,

and alternatives falling within the spirit and scope of the invention as defined by

the following appended claims.